pected. These are discussed in a recent note of Cini, Gatto, Goldwasser, and Ruderman.[12] Among the four terms discussed by these authors, the direct interaction and the p-wave terms disappear for zero meson momentum and the difference between the two cross sections arises from the "recoil term" which has its origin in the magnetic moments of the nucleons. Adopting the results of Baldin's analysis quoted in the last reference,[12] the ratio $\sigma(\gamma+n\rightarrow\pi^-+p)/\sigma(\gamma+p\rightarrow\pi^++n)\cong 1.4$ at threshold, indicating that

$$\sigma(\gamma+n)/\sigma(\gamma+p)=1.4=[(1+\tfrac{1}{2}|R|)/(1-\tfrac{1}{2}|R|)]^2.$$

Here $\frac{1}{2}|R|$ is the relative value of the "recoil term" with respect to the "gauge invariant term." Hence $|R|\cong 0.2$ and the $\gamma+p$ cross section should be increased by about 20% to eliminate the magnetic moment "recoil term." The electric polarizability on a purely static basis is 20% greater than without the correction. For the limit of a plane wave with infinite wavelength, the factor 1.4 gives the correction. In neither case is the correction sufficient to affect the general conclusion of this note.

[12] Cini, Gatto, Goldwasser, and Ruderman, Nuovo cimento (to be published). It is desired to thank Dr. Goldwasser for a preprint of this note and for its discussion.

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Experiments Concerning the Low-Energy States of the O^{19} Nucleus*

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Angular distributions have been measured for three groups of protons from the $O^{18}(d,p)O^{19}$ reaction, those leaving O^{19} in its states at 0, 0.096, and 1.47 Mev. Deuteron energies of 1.74 and 2.50 Mev in the laboratory system were used. The distributions of protons leaving O^{19} in its ground state and in its 1.47-Mev state are characteristic of stripping and indicate the formation of the ground state by an $l=2$ neutron and of the 1.47-Mev state by an $l=0$ neutron. However, the distribution of protons leaving O^{19} in its 0.096-Mev state does not lend itself to a stripping interpretation.

It has been found that the γ decay of the 1.47-Mev state of O^{19}, following the formation of this state in the $O^{18}(d,p)O^{19}$ reaction, proceeds mostly to the 0.096-Mev state. The mean life of the 0.096-Mev state has been measured by observing the decay in flight of recoiling excited O^{19} nuclei and is found to be $1.75(1\pm0.16)\times10^{-9}$ second. These observations restrict the likely assignments of spin and parity for the 0.096-Mev state to $\frac{3}{2}^{\pm}$ or $\frac{5}{2}^{+}$.

I. INTRODUCTION

The intermediate-coupling shell model calculations of Elliott and Flowers[1] and of Redlich[2] for mass 19 nuclei make similar predictions about the presence of even-parity low-energy states in O^{19} and about the properties these states should have. In particular, the work of Elliott and Flowers predicts that the O^{19} ground state should have a spin and parity of $\frac{5}{2}^+$ and in addition that there should be two states, having spins and parities of $\frac{1}{2}^+$ and $\frac{3}{2}^+$, respectively, lying about 0.5 Mev above the ground state.

At the time the present experiments were undertaken, it was known from experiments on the β decay of the O^{19} ground state that it was likely that this state had a spin and parity of $\frac{5}{2}^+$, although another possibility, $\frac{3}{2}^+$, was rejected only because β decay to the $\frac{1}{2}^+$ ground state of F^{19} appeared to be forbidden.[3,4] It was also known that there were two low-energy excited states of O^{19}, one at an excitation energy of 0.096 Mev and one at 1.47 Mev. A study of the $O^{18}(d,p)O^{19}$ reaction in terms of the stripping process had clearly indicated that the 1.47-Mev state was a $\frac{1}{2}^+$ state[5] and thus was possibly one of the predicted even-parity states, displaced in energy. However, little had been learned about the state at 0.096 Mev. The experiments described here were performed with the hope of revealing more of the properties of these three low-energy states of O^{19}.

II. ANGULAR DISTRIBUTIONS OF PROTONS FROM THE $O^{18}(d,p)O^{19}$ REACTION

Butler and others have pointed out that if certain approximations are valid, a (d,p) reaction will proceed by stripping.[6,7] If this is the case, a measurement of the proton angular distribution will enable one to determine the parity of the final state relative to that of the initial state and to restrict the spin of the final state to a few

* Supported in part by the joint program of the Office of Naval Research and the U. S. Atomic Energy Commission.

[1] J. P. Elliott and B. H. Flowers, Proc. Roy. Soc. (London) **A229**, 536 (1955).
[2] M. G. Redlich, Phys. Rev. **98**, 199 (1955); **99**, 1427 (1955).
[3] F. Ajzenberg and T. Lauritsen, Revs. Modern Phys. **27**, 77 (1955).
[4] Toppel, Wilkinson, and Alburger, Phys. Rev. **101**, 1485 (1956).
[5] Stratton, Blair, Famularo, and Stuart, Phys. Rev. **98**, 629 (1955).
[6] S. T. Butler, *Nuclear Stripping Reactions* (Horwitz, Sydney, 1957).
[7] R. Huby, in *Progress in Nuclear Physics*, edited by O. R. Frisch (Academic Press, Inc., New York, 1953), Vol. 3, p. 177.

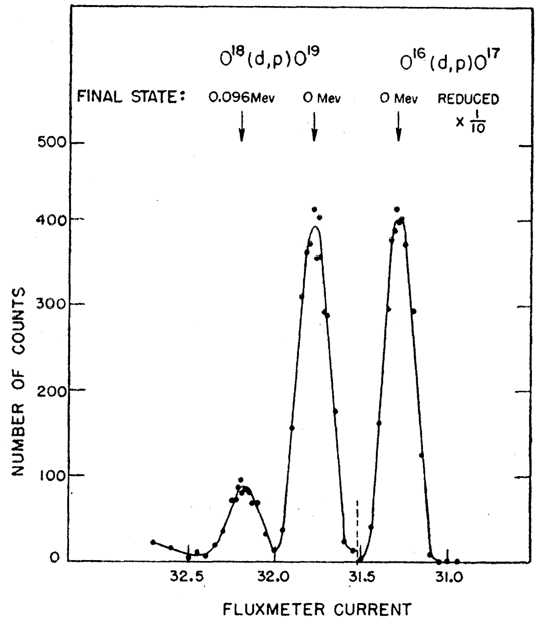

FIG. 1. Representative proton momentum spectrum at a laboratory deuteron energy of 2.50 Mev and laboratory observation angle of 90°. The abscissa, fluxmeter current, is inversely proportional to the proton momentum.

possible values if the spin of the initial state is known. The principal purpose of the work described below was to see what role stripping plays in the formation of the ground and 0.096-Mev states of O^{19} and to what degree the application of stripping theory gives additional information concerning the spin and parity of these states, with the knowledge that the ground state of O^{18} has zero spin and even parity.[3]

(A) Relative Yields

The relative angular distributions of protons leaving O^{19} in its ground and 0.096-Mev states were measured at a bombarding deuteron energy of 2.50 Mev. This energy is given in the laboratory system, as are the rest of the deuteron energies appearing in this article. Although this deuteron energy is low compared to the energies for which stripping theory is expected to be valid, it was believed that at least some of the qualitative features of stripping would appear. Similar angular distribution measurements were made at a deuteron energy of 1.74 Mev for the same two proton groups as above and also for the group leaving O^{19} in its 1.47-Mev state. These measurements at 1.74 Mev were needed for the experiments described in Parts III and IV of this article. It was expected, to be sure, that these latter distributions would show less resemblance to stripping distributions than the ones at 2.50 Mev.

The bombarding deuterons were accelerated by the Kellogg Laboratory 3-Mv Van de Graaff generator and were selected in energy by an electrostatic analyzer.

Thin targets were called for in this experiment in order that the proton groups from the ground and 0.096-Mev states might be resolved from one another and resolved from the group due to the $O^{16}(d,p)O^{17}$ reaction which leaves O^{17} in its ground state.[3,5] Thin target backings were necessary for measurements at forward angles in order to allow the protons to pass through the target without excessive energy loss and straggling.

The targets used were thin self-supporting nickel foils having a central region oxidized with O^{18}-enriched oxygen. The O^{18}:O^{16} ratio of the oxygen was approximately 1:5. The foils were either 500 A or 1000 A nickel foils which were supplied by the Chromium Corporation of America on copper backings. One procedure that was used for preparing the foils in supporting frames has been described by Bashkin and Goldhaber.[8] However, for most of the targets an alternative procedure was used which involved floating the foil on the acid solution used to dissolve the copper backing and on the wash water which was substituted for the acid. The foil was lifted from the surface of the water by means of the supporting frame on which it was to be mounted. The foils were oxidized by using the technique described by Holmgren *et al.*[9] This technique involved heating the foils in an oxygen atmosphere with a focused spot of light from a projection lantern.

The outgoing protons were resolved in momentum by means of a 180° double-focusing magnetic spectrometer with an acceptance solid angle of 0.00624 steradian. The spectrometer was arranged to transmit

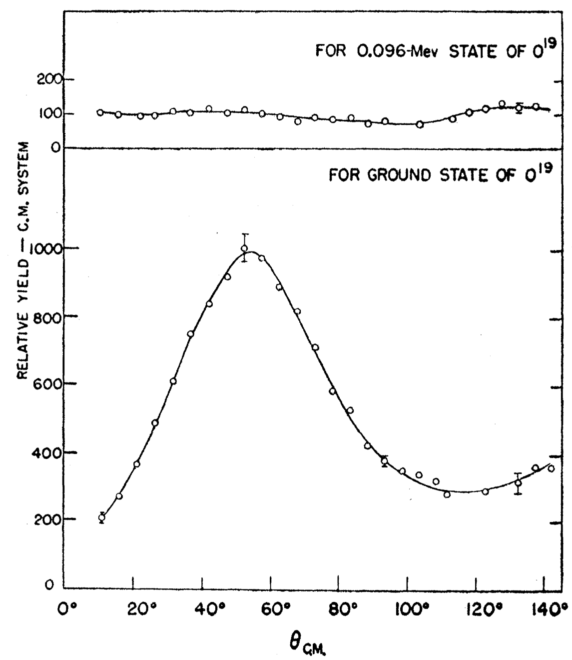

FIG. 2. Proton angular distributions for the $O^{18}(d,p)O^{19}$ reaction at a laboratory deuteron energy of 2.50 Mev.

[8] S. Bashkin and G. Goldhaber, Rev. Sci. Instr. **22**, 112 (1951).
[9] Holmgren, Blair, Famularo, Stratton, and Stuart, Rev. Sci. Instr. **25**, 1026 (1954).

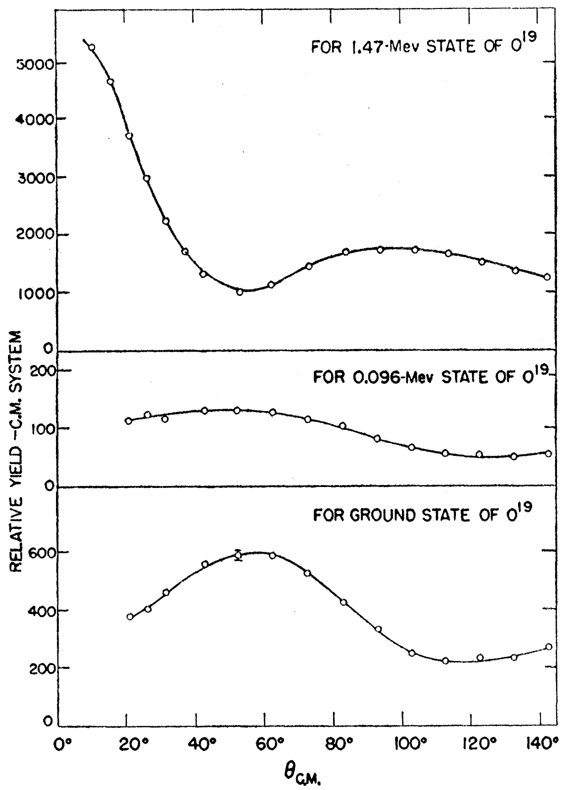

FIG. 3. Proton angular distributions for the $O^{18}(d,p)O^{19}$ reaction at a laboratory deuteron energy of 1.74 Mev.

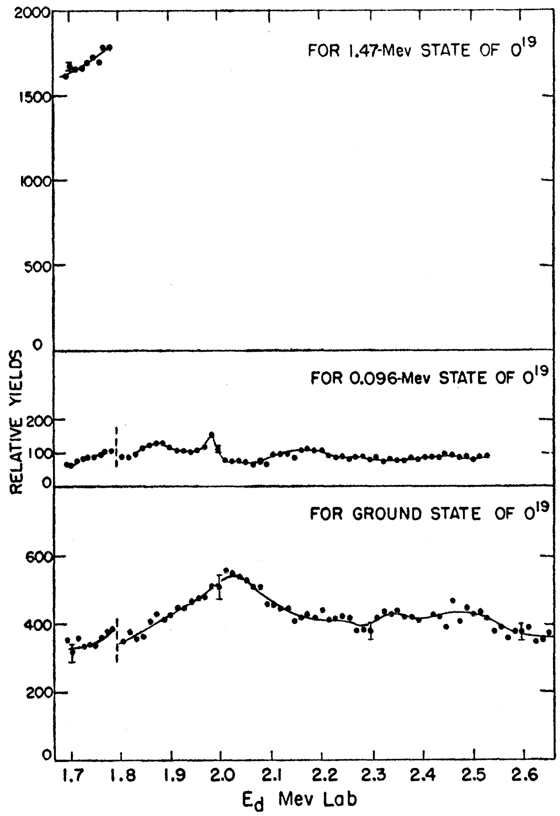

FIG. 4. Proton excitation curves for the $O^{18}(d,p)O^{19}$ reaction at a laboratory observation angle of 90°.

protons within a momentum interval equal in size to about 0.9% of the total proton momentum. This interval was chosen to be a little larger than the momentum spread within any one group for most of the measurements but smaller than the momentum interval between any two groups. A representative momentum spectrum recorded at a laboratory angle of 90° and deuteron energy of 2.50 Mev is shown in Fig. 1. The abscissa, fluxmeter current, is inversely proportional to the proton momentum.

The protons which were transmitted by the spectrometer were detected in a thallium-activated cesium iodide scintillation crystal roughly 0.003 inch thick. An aluminum foil in front of the detector served to exclude from the detector any deuterons which were transmitted by the spectrometer along with the protons.

The resulting proton angular yields were converted to center-of-mass coordinates and are shown in Figs. 2 and 3. In addition, excitation curves for the groups leaving O^{19} in its ground and 0.096-Mev states were measured at a laboratory angle of 90° for deuteron energies between 1.7 and 2.6 Mev in the laboratory system. The excitation curves are shown in Fig. 4.

The portions of the excitation curves to the left and right of the vertical dashed lines at 1.8 Mev were measured at different times and have been normalized to each other by means of a comparison of yields from the same target at 1.74 Mev and 2.50 Mev.

At the same time that some of the above measurements were made, the proton group from the $O^{16}(d,p)O^{17}$ reaction leaving O^{17} in its ground state was observed for reference purposes. Figure 5 gives the angular distribution of this group in center-of-mass coordinates for a deuteron energy of 2.50 Mev, and Fig. 6 gives the excitation curve at a laboratory angle of 90° for deuteron energies between 1.8 and 2.7 Mev. The information in Fig. 6 has been supplemented by some additional data, shown by the solid circles, which were obtained using a scattering chamber and a target prepared from natural oxygen.

The relative yields for the various curves showing the $O^{18}(d,p)O^{19}$ reactions were measured with several different targets but have all been normalized to each other. The same is true for the yields in the two curves showing the $O^{16}(d,p)O^{17}$ reaction.

One of the major sources of error for some of these yields is thought to have been the slow loss of oxygen from the target during bombardment. This loss seemed to occur with beam current intensities of the order of 0.1 microampere per square millimeter. The effect of the loss was to cause not only a slow decrease in the yields, but also an increase in the fluctuations in the yields, since

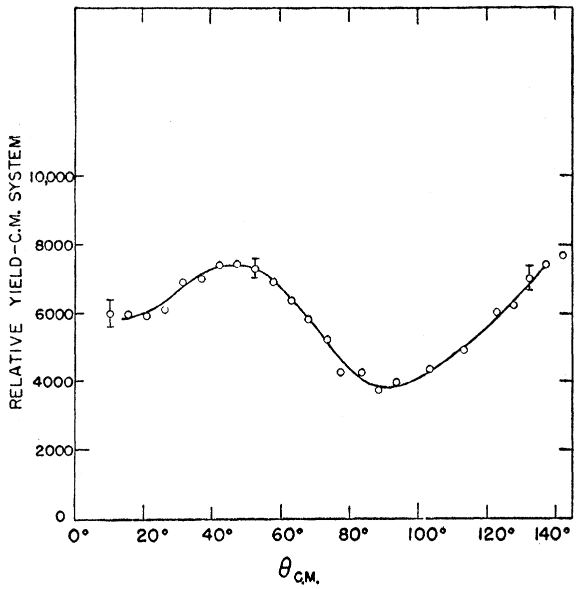

FIG. 5. Proton angular distribution at a laboratory deuteron energy of 2.50 Mev for the $O^{16}(d,p)O^{17}$ reaction which forms the ground state of O^{17}.

the target tended to become nonuniform and the beam did not strike precisely the same spot each run. Other sources of error which have been considered are those due to counting statistics and those involved in the normalization of runs using different target spots.

Standard deviations for the uncertainties in the relative yields were computed for a few representative points in each curve and have been plotted where they exceed the size of the open circles. For the curves in which these deviation symbols are absent it is to be understood that the relative uncertainties are thought to be small. In addition to these errors in the relation between the points along an individual curve there are errors involved in the normalization of one curve for a given target nucleus to another for the same target nucleus. The standard deviations for the normalization factors are all thought to be approximately $\pm 3\%$.

The deuteron energy scale has been corrected to give the energy at the center of the target. It is estimated that the uncertainty in this energy scale is approximately $\pm 0.5\%$.

Total relative yields were obtained for each of the proton groups by integrating the angular relative yields over the sphere. The results are given in Table I. The normalization of these total yields is such that they represent yields per sphere if the angular yields are regarded as representing yields per steradian. An attempt was made to include in the standard deviations stated in Table I the uncertainties due to the lack of knowledge about the shape of the angular distributions at the far forward and far backward angles.

TABLE I. Total relative yields.

Reaction	Final-state excitation energy Mev	Deuteron energy Mev	Total relative yield
$O^{18}(d,p)O^{19}$	0	1.74	$4820(1\pm0.03)$
		2.50	$6610(1\pm0.03)$
	0.096	1.74	$1140(1\pm0.05)$
		2.50	$1270(1\pm0.05)$
	1.47	1.74	$20630(1\pm0.03)$
$O^{16}(d,p)O^{17}$	0	2.50	$74700(1\pm0.02)$

(B) Absolute Cross Sections

Measurements of the absolute cross sections for the $O^{16}(d,p)O^{17}$ reaction were made independently of the measurements described above, using thick targets of both SiO_2 and KNO_3. These measurements yielded a value of $8.7(1\pm0.07)$ millibarns per steradian for a laboratory angle of 90° and deuteron energy of 2.50 Mev. As a result the relative angular yields for this reaction may be converted to millibarns per steradian and the total yields to millibarns by dividing them by $455(1\pm0.08)$. The cross section obtained above is consistent with the value $8.6(1\pm0.15)$ mb/sterad obtained by Grosskreutz for the same energy and angle.[10] However, the cross sections derived by converting the relative yields to millibarns per steradian are approximately 14% lower than those obtained by Stratton *et al.* at the two points of comparison available.[5]

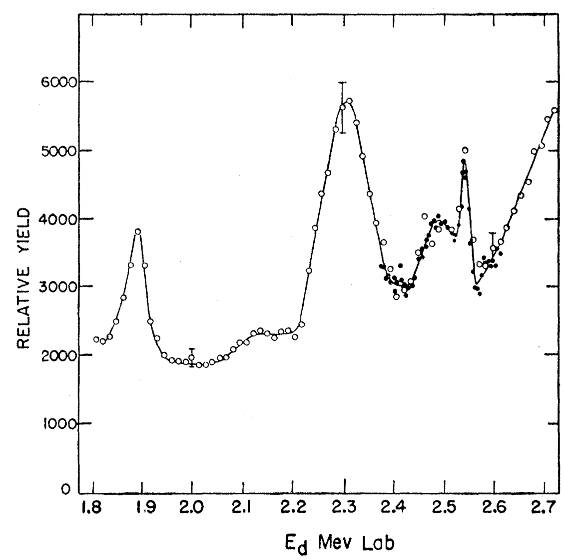

FIG. 6. Proton excitation curve at a laboratory angle of 90° for the $O^{16}(d,p)O^{17}$ reaction which forms the ground state of O^{17}.

The cross sections for the $O^{18}(d,p)O^{19}$ reactions were measured relative to the $O^{16}(d,p)O^{17}$ cross sections. Unfortunately the O^{18} enrichment of the thin oxygen targets was not known accurately. The measurement was made by first comparing the yield of the $O^{16}(d,p)O^{17}$

[10] J. C. Grosskreutz, Phys. Rev. **101**, 706 (1956).

reaction with that of the $O^{18}(p,\alpha)N^{15}$ reaction forming the ground state of N^{15}, using a thin tungsten oxide target prepared from natural oxygen. Then the $O^{18}(p,\alpha)N^{15}$ and $O^{18}(d,p)O^{19}$ yields from an O^{18}-enriched target were compared. The value obtained for the differential cross section at a laboratory angle of 90° and deuteron energy of 1.74 Mev for the $O^{18}(d,p)O^{19}$ reaction forming the ground state of O^{19} is $3.5(1\pm0.10)$ mb/sterad. As a result the relative angular yields for the $O^{18}(d,p)O^{19}$ reactions may be converted to millibarns per steradian and the total yields to millibarns by dividing them by $96(1\pm0.11)$. The intermediate $O^{18}(p,\alpha)N^{15}$ cross section was found to be $5.2(1\pm0.09)$ mb/sterad at a laboratory angle of 90° and deuteron energy of 2.13 Mev. This value may be compared to the value $4.7(1\pm0.2)$ mb/sterad obtained by Hill and Blair for the same energy and angle.[11]

(C) Discussion of Proton Angular Distribution Results

The angular distribution of protons leaving O^{19} in its ground state at a deuteron energy of 2.50 Mev shows the forward maximum typical of a stripping distribution and indicates the capture of an $l=2$ neutron by O^{18} to form the ground state of O^{19}. The $l=2$ assignment is based on a comparison of the angular position of the maximum of the experimental distribution with that of the distribution given by the simple Butler theory. This comparison was carried out using the tables of Lubitz.[12] It was found that a value of r_0 equal to 5.7×10^{-13} cm must be used in the theoretical expression for $l=2$ to make the maxima coincide. The corresponding angular distribution at a deuteron energy of 1.74 Mev shows somewhat less pronounced forward peaking in agreement with the expectation that the theory becomes less applicable as the deuteron energy decreases.

An $l=2$ neutron may combine with the 0^+ ground state of O^{18} to form either a $\frac{3}{2}^+$ or a $\frac{5}{2}^+$ state of O^{19}. These possibilities for the ground state of O^{19} are quite consistent with the β-decay results. It is unfortunate that the stripping results do not strengthen the preference of $\frac{5}{2}^+$ over $\frac{3}{2}^+$ that is derived from the β-decay work.

The angular distribution of the weak proton group leaving O^{19} in its 0.096-Mev state is almost isotropic for a deuteron energy of 2.50-Mev. The absence of the characteristics of stripping suggests that the reduced width for the formation of this state from the ground state of O^{18} plus a neutron is small.

Ahnlund finds that at a deuteron energy of 0.88 Mev the intensity of the proton group leaving O^{19} in its 0.096-Mev state rises significantly in the forward direction.[13] Some sign of this tendency can be seen in Fig. 3 at a deuteron energy of 1.74 Mev. Although Popić analyzes Ahnlund's data in terms of an $l=1$ stripping distribution,[14] it is perhaps not clear that the forward rise can be understood so simply, in view of the tendency of this effect to disappear at higher deuteron energies.

The proton distribution leaving O^{19} in its state at 1.47 Mev appears to show characteristics of an $l=0$ stripping shape, even though the deuteron energy of 1.74 Mev is quite low for stripping theory to apply well. This l value is in agreement with the value determined by Stratton *et al.*, at a deuteron energy of 3.01 Mev.[5]

III. GAMMA-RAY TRANSITIONS IN O^{19}

The experiment described in this part was undertaken to determine the relative probabilities for the γ decay of the 1.47-Mev state to the ground and 0.096-Mev states. The procedure was to measure the yield of the 0.096-Mev γ rays resulting from the $O^{18}(d,p)O^{19}$ reaction in relation to the total yields of protons leaving O^{19} in its 0.096-Mev and 1.47-Mev states. It was assumed here that there were no other excited states of O^{19} being produced in this reaction leading to the emission of additional 0.096-Mev γ rays.[15]

This experiment was carried out in part with the equipment that was used to measure the proton angular distributions. The proton spectrometer was placed at a laboratory angle of 30° and observed the $O^{18}(d,p)O^{19}$ proton group which leaves the O^{19} nucleus in its 1.47-Mev state. At the same time 0.096-Mev γ rays were detected in a scintillation counter placed at a laboratory angle of 90°.

The scintillation counter consisted of a cylinder of thallium-activated sodium iodide $\frac{1}{2}$ inch long and 1 inch in diameter fastened to a DuMont 6292 photomultiplier tube. The counter was placed in a lead shield which was lined with 0.010-inch tantalum sheet next to the lead and two layers of 0.018-inch tin sheet inside the tantalum. This lining served to degrade the energy of fluorescent x-radiation from the lead, which would have contributed a large background on the low-energy side of the 0.096-Mev photopeak. Pulses from the scintillation counter were sorted in a 100-channel pulse-height analyzer.

The bombarding deuteron energy was 1.74 Mev. Because proton angular distributions had been measured at this energy, it was possible to infer from the number of protons counted the total number of O^{19} nuclei formed in the 0.096-Mev and 1.47-Mev states.

The total 0.096-Mev γ-ray yield was calculated from the number of counts recorded in the γ-ray counter assuming that the emission was isotropic in the laboratory system. In so far as compound nuclear processes are involved in the formation of the 0.096-Mev state, the high excitation energy in F^{20} and the absence of marked resonance behavior in the excitation function make it likely that many states of different angular

[11] H. A. Hill and J. M. Blair, Phys. Rev. **104**, 198 (1956).
[12] C. R. Lubitz, *Numerical Table of Butler-Born Approximation Stripping Cross Sections* (University of Michigan, Ann Arbor, Michigan, 1957).
[13] K. Ahnlund, Arkiv Physik **10**, 425 (1956).
[14] R. V. Popić, Nuovo cimento **4**, 1597 (1956).
[15] Thirion, Cohen, and Whaling, Phys. Rev. **96**, 850A (1954).

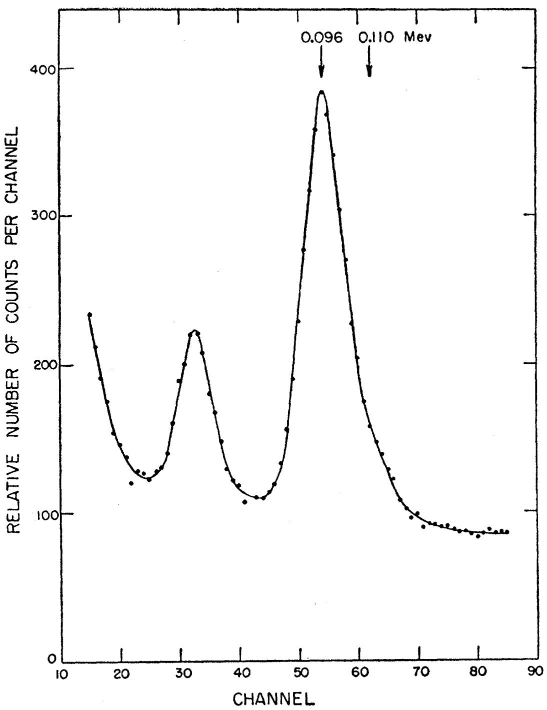

FIG. 7. Representative γ-ray pulse-height spectrum for the experiment of Part III showing the 0.096-Mev photopeak.

momenta contribute to this reaction in no simple phase relationship and that no marked angular effects are produced. The 1.47-Mev state, of course, is thought to have a spin of $\frac{1}{2}$, and so any radiation which follows its formation must be isotropic.

A representative γ-ray pulse height spectrum showing the 0.096-Mev photopeak is plotted in Fig. 7. The smaller peak centered about channels 32 and 33 may be due to the inelastic scattering of neutrons by I^{127} in the scintillation crystal, in which γ rays of about 60 kev in energy are produced.

In analyzing the γ-ray spectra, care was taken not to include any counts which might have been associated with 0.110-Mev γ radiation from F^{19}. Such radiation might have resulted from the $O^{18}(d,n)F^{19}$ reaction. Because the photopeak of the 0.096-Mev radiation had a width at half-maximum of about 16%, the two γ rays could not be well resolved from one another. The only evidence for the presence of any 0.110-Mev γ radiation is a broadening of the low part of the high-energy side of the 0.096-Mev photopeak.

The ratio of the number of protons leaving O^{19} in its 0.096-Mev state to the number of 0.096-Mev γ rays was found to be $0.05(1\pm0.1)$ and the corresponding ratio for the 1.47-Mev state was found to be $0.91(1\pm0.14)$. A major part of each of the assigned uncertainties, $\pm10\%$, lies in the background subtraction procedure.

These measurements make it plausible that the 1.47-Mev state of O^{19} decays almost entirely to the 0.096-Mev state in preference to the ground state. This observation would suggest that because an $E2$ transition is allowed to the ground state the transition to the 0.096-Mev state is $E1$ or $M1$ with $E2$ a third, less likely possibility. These alternatives would allow the 0.096-Mev state to have a spin and parity of $\frac{1}{2}^{\pm}$ or $\frac{3}{2}^{\pm}$, with $\frac{5}{2}^{+}$ a less likely possibility. The lifetime experiment described below is believed to rule out the possibilities of $\frac{1}{2}^{\pm}$, if the ground state has in fact a spin of $\frac{5}{2}$.

IV. LIFETIME OF THE 0.096-MEV STATE OF O^{19}

(A) Experiment

The measurement of the lifetime of the 0.096-Mev state of O^{19} was carried out using a recoil technique. This involved observing directly the distance that excited O^{19} nuclei, recoiling from the $O^{18}(d,p)O^{19}$ reaction, traveled in vacuo at known velocities before decaying by the emission of 0.096-Mev γ radiation. A detail of the apparatus is shown in Fig. 8.

In this experiment a beam of 1.74-Mev deuterons from the Kellogg Laboratory 2-Mv Van de Graaff generator was passed through a thin, self-supported, O^{18}-enriched NiO target such as was used for the proton angular distributions. A nickel foil thickness of 500 A was chosen in order that the recoiling O^{19} atoms would not lose a large portion of their velocity in the target. The beam spot was typically a square 0.06 inch on a side.

The results of Part III indicate that under these conditions most of the 0.096-Mev γ rays arise from O^{19} nuclei which are first produced in the 1.47-Mev state. All of the O^{19} nuclei so produced recoil initially in the forward direction within a cone of half-angle 48°. As these excited recoil nuclei decay to the 0.096-Mev state additional momentum is imparted to the nucleus, but this momentum is small compared to the total momen-

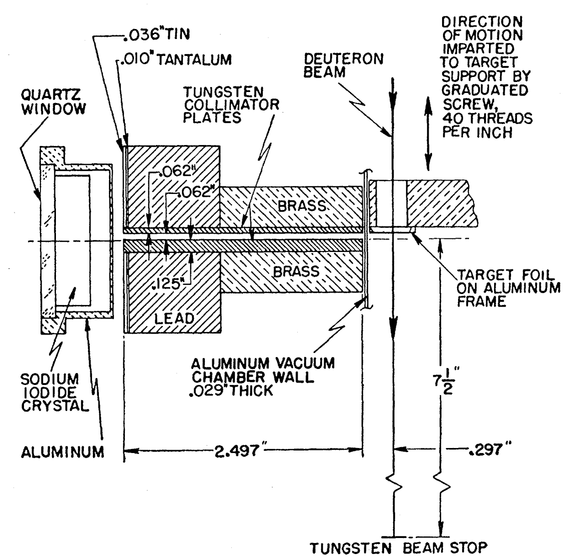

FIG. 8. Detail of the recoil lifetime apparatus.

tum of the nucleus and has been neglected here. The O^{19} nuclei which are formed directly in the 0.096-Mev state also recoil in the forward direction but within a cone of half-angle 79°.

The 0.096-Mev γ rays were detected in a square prism of thallium-activated sodium iodide 1 inch square by $\frac{3}{8}$ inch which was shielded from stray radiation by lead lined in the fashion described in Part III. The pulses from the DuMont 6292 photomultiplier were sorted in a 100-channel pulse-height analyzer.

The γ-ray counter was provided with a collimator through which could be seen a narrow region of the space just following the target. For reasons of convenience it was the target rather than the collimator and counter that was moved to vary the distance between the target and the region seen by the counter. The target was moved and its position measured by means of a precision screw having a pitch of 40 threads per inch. The critical edges of the collimator were made of tungsten. These edges were very sharp for the low-energy 0.096-Mev γ radiation compared to the range of distances from the target being measured.

Figure 9 shows representative γ-ray pulse-height spectra for three different target positions, each spectrum being taken for the same number of incident deuterons. These spectra are accompanied by a reference spectrum, shown in Fig. 10, which is due to 0.088-Mev γ rays from a Cd^{109} source and which was recorded with the same

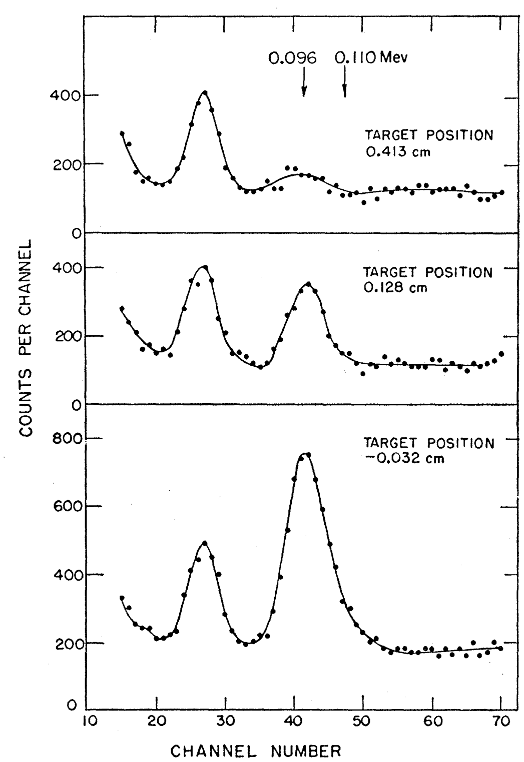

FIG. 9. Representative γ-ray pulse-height spectra for the recoil lifetime experiment showing the 0.096-Mev photopeak for various target positions.

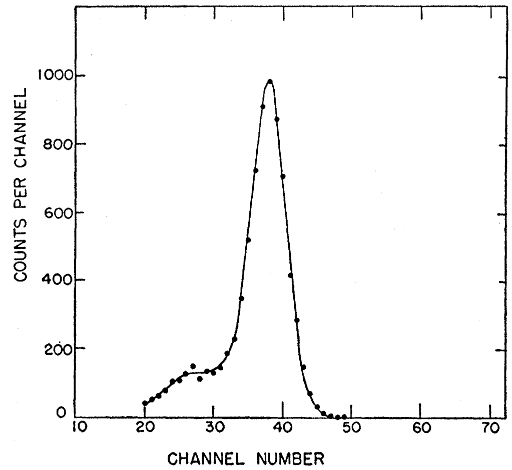

FIG. 10. Reference γ-ray pulse-height spectrum for the recoil lifetime experiment showing the photopeak of 0.088-Mev γ rays from a Cd^{109} source.

pulse amplification as the spectra in Fig. 9. There existed the possibility in this experiment as in the γ-ray yield measurements of Part III that 0.110-Mev γ radiation from F^{19} was present, and some evidence of this radiation may be seen in the spectrum at the bottom of Fig. 9 where the low part of the high-energy side of the peak is less steep than that of the Cd^{109} reference spectrum in Fig. 10.

For each target position the relative number of 0.096-Mev γ rays per fixed number of incident deuterons was computed, taking care to exclude any counts from unwanted 0.110-Mev radiation. These numbers are represented by solid circles plotted in Fig. 11 as a function of the relative target position. The normalization of the ordinate scale and the choice of origin for the abscissa scale in Fig. 11 were not determined by the experiment but were chosen so as to give the best fit to the smooth curve which appears in the same figure. This smooth curve is a calculated curve and is discussed below. The ordinates of the four lowest points were appreciably affected by the method of background subtraction used in the analysis of the pulse-height spectra. The ordinate of the lowest of these points has perhaps an uncertainty of about ±30% for this reason.

In view of the fact that most of the 0.096-Mev γ radiation is preceded by 1.37-Mev radiation from the 1.47-Mev state, the experiment described so far does not distinguish which of the two excited states involved is showing the observed lifetime. An attempt was made to use the same apparatus with a modified arrangement of scintillation crystal and shielding to verify directly that the 1.37-Mev γ radiation does not itself show a lifetime comparable to that already observed.

The results were rather inconclusive. This was due in part to the smallness of the number of counts in the full-energy peak of the 1.37-Mev γ-ray spectrum and to the presence of a relatively large background which

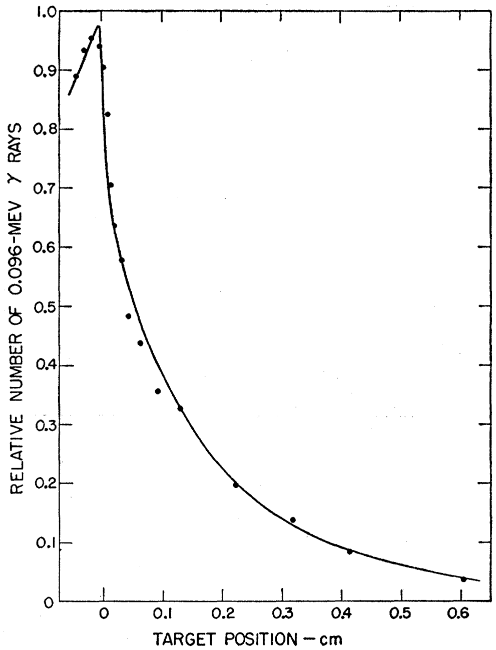

FIG. 11. The relative number of 0.096-Mev γ-ray counts as a function of target position in the recoil lifetime experiment. The solid circles represent experimental points. The smooth curve was calculated for a mean life of 1.70×10^{-9} second.

climbed steeply in the low-energy direction. In addition, the collimator edges were much less sharp for this γ ray than they were for the low-energy one. The rate of decrease of the 1.37-Mev γ-ray intensity as the target was moved appeared to be perhaps somewhat greater than 3 times the rate for the 0.096-Mev γ ray. It is believed that this rate was not significantly different from the rate that one would have observed for a γ ray of this energy emitted from a state of vanishing lifetime.

(B) Calculation of the Mean Life

The smooth curve which appears in Fig. 11 is a curve calculated for a mean life of 1.70×10^{-9} second. It was assumed for this calculation that all of the O^{19} nuclei formed in the 1.47-Mev state decay to the 0.096-Mev state rather than to the ground state. It was assumed also that the lifetime of the 1.47-Mev state is short compared to the lifetime of the 0.096-Mev state. A third assumption was that the 0.096-Mev γ rays were emitted isotropically in the system of the recoiling nucleus. This assumption was thought to be justified by the same considerations that were presented in Part III to justify the assumption of isotropy in the laboratory system.

The first step in making this calculation was to determine the direction and velocity of an excited O^{19} recoil nucleus in terms of the direction of the proton emitted with it. It was then necessary to correct the recoil velocity for the loss of velocity suffered in escaping from the target. No attempt was made, however, to correct for any change of direction of motion of the O^{19} recoil in the target. Next, the probability that an excited recoil nucleus with a mean life τ would reach a certain perpendicular distance from the target before decaying was computed as a function of the direction of emission of the coincident proton. Then, a sum over all proton directions was performed using the proton angular yields that had been measured in Part II for the deuteron energy of 1.74 Mev. This sum may be called $N(z/\tau)$, where z is the perpendicular distance from the target. $N(z/\tau)$ was evaluated by numerical means for each of the two modes of formation of the 0.096-Mev state, and the results were added together to give a function that may be called $N_S(z/\tau)$. The function that describes the number of recoils that decay in view of the counter is given approximately by $N_S(z/\tau)-N_S((z+\Delta z)/\tau)$, where Δz is the interval of z along the beam axis that is seen by the counter. This last function is the one which was used to construct the smooth curve, for which the abscissa, target position, corresponds to z.

In order to correct for the loss of recoil velocity in the target it was necessary to determine $dv/d\rho$, the rate of change of an atom's velocity per unit surface density of stopping material, for O^{19} atoms being slowed by the nickel oxide target and by the carbon surface layer which appeared on the target during bombardment. The velocities of the recoils in this experiment lay between 0 and 2.5×10^8 cm/sec.

A survey of some of the literature[16–20] on the stopping of moving atoms led to the assumption that $dv/d\rho$ depends on velocity as $1/v$ for v less than 1.2×10^8 cm/sec and is constant for greater velocities with a smooth connection at 1.2×10^8 cm/sec. The following values were adopted for $dv/d\rho$ in the constant region:

$$O^{19} \text{ in NiO}: dv/d\rho=4.9\times10^5 \text{ cm sec}^{-1}/(\mu\text{g nickel cm}^{-2}),$$
$$O^{19} \text{ in C}: \quad dv/d\rho=9.3\times10^5 \text{ cm sec}^{-1}/(\mu\text{g carbon cm}^{-2}).$$

A standard deviation of $\pm30\%$ was assigned to the velocity scale of the resulting functions for $dv/d\rho$.

The surface density of nickel in the target was determined from the nominal thickness of the foil, 500 A, and by elastic proton scattering to be $49(1\pm0.1)$ μg nickel/cm^2. The calculations were made by making the approximation that all of the recoils originated in the middle of the target layer and thus had to pass through a NiO layer corresponding to one half of the nickel density measured above. The surface density of carbon on both sides of the target combined was determined by means of the $C^{12}(d,p)C^{13}$ reaction. The value obtained for the surface density of carbon after the target had been used

[16] W. Whaling, in *Handbuch der Physik*, edited by S. Flügge (Springer-Verlag, Berlin, 1958), Vol. 34, p. 193.
[17] Devons, Manning, and Towle, Proc. Phys. Soc. (London) **A69**, 173 (1956).
[18] Evans, Stier, and Barnett, Phys. Rev. **90**, 825 (1953).
[19] P. M. S. Blackett and D. S. Lees, Proc. Roy. Soc. (London) **134**, 658 (1932).
[20] K. O. Nielsen, in *Electromagnetically Enriched Isotopes and Mass Spectrometry*, edited by M. L. Smith (Academic Press, Inc., New York, 1956), p. 68.

for a set of recoil runs was about 4 ± 3 $\mu g/cm^2$. Assuming that the carbon layer built up linearly with bombardment during the recoil runs, the average recoil had to pass through a layer of roughly one quarter this thickness, and the correction to its velocity for the carbon layer was very small.

The final value of the mean life, which was determined from the set of runs shown in Fig. 11 and from a set measured with a 0.125-inch collimator spacing, is $1.75(1\pm0.16)\times10^{-9}$ second. The standard deviation is based mainly on two sources of uncertainty. The first source was mentioned earlier and concerns the amount of background to be subtracted from the γ-ray photopeaks. It is thought that this uncertainty produces an uncertainty in the lifetime of about $\pm10\%$.

The second source is the uncertainty in the rate of stopping of O^{19} atoms in the target. It is estimated that this uncertainty produces an uncertainty in the time scale of the calculated curve of perhaps $\pm12\%$. This is, of course, an oversimplification of the situation since the uncertainty is not only one of time scale but also of shape, due to the fact that the low-velocity recoils are influenced more than the high-velocity ones. It may be seen in Fig. 11 that the calculated curve is not of quite the proper shape to fit the points well, lying above the experimental points for target positions in the region of 0.08 cm. It is found that if lower values of $dv/d\rho$ and a correspondingly lower value of mean life are used the shape agreement becomes worse. On the other hand, if larger values of $dv/d\rho$ and a correspondingly larger value of mean life are used the agreement is improved. These considerations were given weight in the assignment of a lifetime, but it is believed that they are not sure enough to dictate the values of $dv/d\rho$ to be used. It seems possible that the inclusion of the effects of large-angle scattering of the moving atoms with velocities less than 1.0×10^8 centimeters per second might also improve the shape of the calculated curve by lowering it for target positions in the region of 0.08 cm without affecting the outer end.

(C) Discussion of the Lifetime Results

If one computes rough single-particle limits for the 0.096-Mev transition in O^{19}, using the formulas given by Blatt and Weisskopf[21] with a radius of $1.5A^{\frac{1}{3}}\times10^{-13}$ cm and without any additional statistical factors, one obtains the following estimates:

Multipolarity	Mean life (sec)
$E1$	1.0×10^{-12}
$M1$	3.6×10^{-11}
$E2$	1.3×10^{-5}

The measured lifetime thus could be that of either a slow $E1$ or $M1$ transition.[22] It is extremely unlikely that it is an $E2$ transition. A dipole transition between the

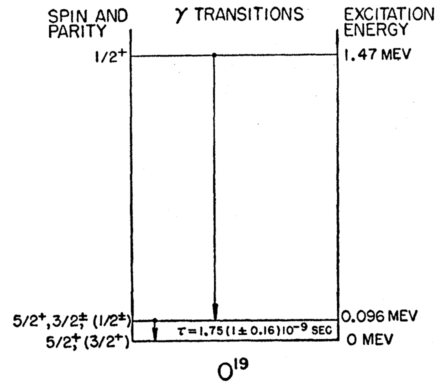

FIG. 12. Energy level diagram for O^{19}.

0.096-Mev state and a spin $\frac{5}{2}$ ground state allows spin $\frac{3}{2}$, $\frac{5}{2}$, or $\frac{7}{2}$ for the former state. However, only the possibilities $\frac{3}{2}^{\pm}$ or $\frac{5}{2}^{+}$ are in agreement with those suggested in Part III.

In regard to the possibility that the 1.47-Mev state might have a mean life of the order of the one observed, it is again useful to take recourse to single-particle estimates. The single-particle estimate for the mean life of an $E2$ transition from the 1.47-Mev state to the ground state is 1.6×10^{-11} second. If it be assumed that the 1.37-Mev transition is at least approximately a power of ten faster than the 1.47-Mev transition, then for the 1.37-Mev transition to have a mean life of the order of 10^{-9} second the speed of the 1.47-Mev transition would have to be more than 100 times slower than the single-particle estimate. It may be noted that among the eight $E2$ transitions in light nuclei listed by Wilkinson[22] only one has a speed relative to its single-particle estimate of this order and that this one is not too well established. It is true, however, as Wilkinson points out, that fast transitions are more likely to have been observed than slow ones. Nevertheless, there appears to be some basis for believing that the lifetime of the 1.47-Mev state is considerably shorter than the measured lifetime.

Some of the conclusions of these experiments and of previous ones are shown in Fig. 12, which represents an energy level diagram for O^{19}.

V. COMPARISON OF RESULTS WITH THEORY

One of the outstanding questions to be answered in connection with the theoretical work of Elliott and Flowers[1] on O^{19} is whether the 0.096-Mev state is indeed the $\frac{3}{2}^{+}$ state that is predicted at roughly 0.5 Mev. The results of several considerations are consistent with this identification. Let it be assumed that the 1.47-Mev state accounts for the $\frac{1}{2}^{+}$ state that is predicted for about the same excitation energy, 0.5 Mev, and that the ground state of O^{19} is the $\frac{5}{2}^{+}$ state that is predicted for the lowest state. First, it may be noted that a spin and parity of $\frac{3}{2}^{+}$ is indeed one of the possibilities for the 0.096-Mev state that is permitted by the experiments described above.

[21] J. M. Blatt and V. F. Weisskopf, *Theoretical Nuclear Physics* (John Wiley & Sons, Inc., New York, 1952), p. 627.

[22] D. H. Wilkinson, Phil. Mag. **1**, 127 (1956).

Second, the theoretical wave functions of Elliott and Flowers for the 0^+ state of O^{18} and for the $\frac{3}{2}^+$ state of O^{19} are consistent with a small reduced width for the formation of the O^{19} state from the O^{18} state plus a neutron and hence with the observed lack of stripping in the formation of the 0.096-Mev state of O^{19}. This relationship may be seen by an examination of the jj-coupling decompositions of the wave functions for the O^{18} ground state and for the $\frac{3}{2}^+$ state of O^{19}. The 0^+ ground state of O^{18} is described as having a configuration for two neutrons outside of an unexcited O^{16} core which is 79% $(d_{\frac{5}{2}})^2$, 6% $(d_{\frac{3}{2}})^2$, and 15% $(s_{\frac{1}{2}})^2$. In order to form a $\frac{3}{2}^+$ state of O^{19} by stripping, a $d_{\frac{3}{2}}$ neutron must be added to this configuration. However, the predicted configuration of the three neutrons outside of the O^{16} core for the $\frac{3}{2}^+$ state of O^{19} is 62% $(d_{\frac{5}{2}})^3$, 33% $(d_{\frac{5}{2}})^2(s_{\frac{1}{2}})$, 2% $(d_{\frac{5}{2}})(d_{\frac{3}{2}})(s_{\frac{1}{2}})$, and 3% $(d_{\frac{5}{2}})^2(d_{\frac{3}{2}})$. Only the last of these four terms is seen to be of the right form for stripping formation.

Third, the lifetime of the $\frac{3}{2}^+$ state has been computed from the wave functions assuming that it lies at 0.096-Mev excitation, and the resulting mean life is 2.2×10^{-9} second in fair agreement with the measured value. The calculation was made assuming that the transition is completely magnetic dipole, and the transition matrix elements were computed from the expressions given by Blatt and Weisskopf.[23] The calculation was considerably simplified by the fact that all of the three nucleons outside of the core are neutrons. Because of this fact the orbital part of the $M1$ operator contributes only by virtue of the motion of the core, and it was found that this contribution is negligible compared to that of the spin part of the operator. Since the transition is magnetic dipole, consideration of the nuclear radius was not needed.

There are perhaps two further experiments which together might indicate a unique assignment of spin and parity for the 0.096-Mev state. One of these is the determination of the internal conversion coefficient of the 0.096-Mev transition. The K-shell conversion coefficient for an $E1$ transition is estimated[24] to be 1.9×10^{-3} while that for an $M1$ transition is estimated to be 5.9×10^{-4}. By distinguishing between these one could hope to determine the multipolarity of the radiation and hence the parity of the 0.096-Mev state.

The other experiment, which should determine the spin of the 0.096-Mev state, is a measurement of the γ-γ angular correlation between the 1.37-Mev and the 0.096-Mev γ rays. If it be assumed that the ground state has spin $\frac{5}{2}$, then a γ-γ angular correlation of $1+0.05P_2(\cos\theta)$ is expected for a $\frac{3}{2}$ state at 0.096 Mev and one of $1+0.23P_2(\cos\theta)$ for a $\frac{5}{2}$ state. This experiment would also provide a test for the $\frac{5}{2}$ spin assignment for the ground state. If the spin of this state were $\frac{3}{2}$ the results of Parts III and IV would allow the 0.096-Mev state to have spin and parity $\frac{1}{2}^\pm$ or $\frac{3}{2}^\pm$ or possibly though very unlikely $\frac{5}{2}^+$. If the spin of the 0.096-Mev state were $\frac{1}{2}$, the correlation would be isotropic, while if it were $\frac{3}{2}$ or $\frac{5}{2}$ the correlation would be $1-0.20P_2(\cos\theta)$.

VI. ACKNOWLEDGMENTS

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[23] Reference 21, p. 599.

[24] W. R. Mills, Jr., thesis, California Institute of Technology, 1955 (unpublished).